Development of Prediction Method of Boundary Layer Bypass Transition using Intermittency Transport Equation

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This paper presents a new RANS-based method for predicting bypass transition of the boundary layer using intermittency transport equation. The base program is based on the boundary-layer analysis code given by Schmidt and Patankar (1988), implemented with Myong-Kasagi $k-\varepsilon$ turbulence model. The intermittency transport equation proposed in this study is the modification of Cho and Chung model (1992) with respect to the diffusion term and empirical model constants. The intermittent behavior of the transitional flow is invoked in the computation when the momentum-thickness based Reynolds number exceed a criterion given by the empirical correlation of Abu-Ghannam and Shaw (1980). The method proposed in this study is applied to the prediction of boundary layer transition under the influence of free stream turbulence and pressure gradient. Through the comparison of the calculated results with the corresponding experimental data, for example ERCOFTAC T3A, the proposed method is proven to have a potential as a predictive tool of FST (free stream turbulence intensity)-induced boundary layer transition.

INTRODUCTION

Boundary layers developing on blades and vanes in turbomachines usually start as laminar boundary layer, and in most situations they eventually become turbulent. Since aerodynamic performance as well as reliability of turbomachines depend on the momentum and heat transfer characteristics of boundary layers, it is crucial for developing competent and marketable turbomachines to make an accurate prediction of the boundary layer evolution, especially boundary layer transition from laminar to turbulent status. The boundary layer transition is significantly influenced by free stream turbulence or any other disturbances such as wake passing. It is a widely accepted idea that the transition governed by the free stream turbulence or wake passing, which is called bypass transition, is a common mode of boundary layer transition in turbomachines. Therefore, proper prediction of the bypass transition is one of the most important and challenging tasks for turbomachine designers.

There have been several modeling concepts for transition prediction. One of the prevailing modeling is the e^n method, applied mostly to external-flow cases. Since it is based on the linear stability theory, it cannot predict the transition induced by non-linear effects such as high free stream turbulence or surface roughness. In other words, the stability-theory based method is less helpful in predicting the bypass transition where external free stream disturbances, bypassing the classic instability mechanism, initiate the non-linear three-dimensional transition process directly.

A number of studies on boundary layer bypass transition prediction have appeared in literature, using low-Reynolds number turbulence models. One of the successful approaches was proposed by Schmidt and Patankar (1988) using Production Term Modification (PTM) method. In their method the production term of turbulent kinetic energy (TKE) for transitional boundary layer was described using an ordinary differential equation of first order that emulated the evolution process of the TKE as delayed first-order system. The approach of Schmidt and Patankar has failed to gain popularity even among the turbomachinery community probably because it requires two parameters in the differential equation to be determined empirically. Some low Reynolds number models have been developed which explicitly contain information on the transition mechanism. Examples of this type of turbulence model are given by Wilcox (1993) and Langtry and Sjolander (2002).

An alternative approach for predicting the bypass transition, which is nowadays being implemented into some of the commercial codes, is the usage of intermittency. The concept of intermittency, a measure of the probability of a given point to be inside the turbulent region, has evolved from the need to distinguish between the uniform and random behaviors of the flow in the intermittent region. The widely accepted function describing the streamwise evolution of the intermittency factor was proposed by Dhawan and Narashima (1958), which has become the foundation of extensive researches in the field of transition modeling.

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In the present study, a RANS based new transport equation of intermittency is proposed by modifying the Cho and Chung (1992) model. The intermittency equation is coupled with the Myong - Kasagi $k-\varepsilon$ model (1988). This paper shows that the new model is able to reproduce the realistic intermittency profile in the streamwise as well as cross-stream directions. In this paper a brief review of related transition model is given in section 2. Section 3 provides the details of the turbulence model and numerical method used in this study. Section 4 shows the comparison of the new transition model against T3 series of experiments of Savill (1993a, 1993b) and the prediction of the $k-\varepsilon-\gamma$ model of Suzen and Huang (2000), $k-\varepsilon$ model of Launder-Sharma (1974), and $k-\omega$ model of Wilcox (1988); Blair and Werle experiments of heat transfer for flat plate zero pressure and favorable pressure gradients (1980,1981) and Danniel and Browne (1981) turbine blade experiment. Section 5 provides the concluding remarks.

NOMENCLATURE

C_f	: skin friction coefficient
C_i	: empirical contants for intermittency transport equation
C_μ	: model constant for eddy viscosity
H_{12}	: shape factor (= δ^*/θ)
h	: heat transfer coefficient
K	: acceleration parameter
k	: turbulent kinetic energy
P_k	: production of turbulent kinetic energy
q_w	: heat flux
Re_x	: Reynolds number based on x
Re_θ	: Reynolds number based on momentum thickness
s	: streamwise distance along the surface from the stagnation point
St	: Stanton number
T_e	: free stream temperature
T_w	: wall temperature
Tu	: turbulence intensity
U_e	: free stream velocity
U_{in}	: inlet velocity
u	: streamwise velocity component
x	: surface length from the leading edge
y^+	: non-dimensional distance from the wall
γ	: intermittency factor
δ	: momentum boundary layer thickness
δ_t	: thermal boundary layer thickness
ε	: dissipation rate
δ^*	: displacement thickness
θ	: momentum thickness
μ	: moleculer viscosity
μ_t	: eddy viscosity
ρ	: density

Subscripts

e	: free stream
tr	: transition onset

TRANSITION MODELS

Preceded by the study of Libby (1975), Byggstoyl and Kollmann (1986) proposed a conditional $k-\varepsilon-\gamma$ model in which momentum equations for the turbulent and irrotational zones were solved along with transport equations of turbulent kinetic energy and its dissipation rate, in consideration of the contribution of the turbulent-irrotational interface to these equations. They solved the intermittency transport equation based on turbulent zone quantities.

Steelant and Dick (1996) proposed another transport equation for intermittency. Steelent and Dick coupled the transport equation with the conditioned Navier-Stokes equations in order to predict transitional flow with zero, favorable and adverse pressure gradients. However, since their approach involves the solution of two sets of strongly coupled equations, this is not compatible with CFD codes.

Cho and Chung (1992) proposed a RANS based new type intermittency model called $k-\varepsilon-\gamma$ model. They modified the Biggstoyl and Kollmann model (1986) by dropping the sink term while including the entrainment effect. This model is much simpler than Biggstoyl and Kollmann model because it is based on the eddy viscosity model. Their turbulence model explicitly incorporated the intermittency effect into the conventional $k-\varepsilon$ turbulence model equations by introducing the additional transport equation for γ . They examined the validity of their model by applying it mainly to free-shear flows such as plane jet, round jet, a plane far wake and plane mixing layer. Good agreements were obtained between the predictions and the experiments, whereas it was not the case for the prediction of wall bounded shear flows.

Wang and Derksen (1999) have used the Cho and Chung $k-\varepsilon-\gamma$ model (1992) to investigate the developing turbulent flow in a pipe. They showed that the transport equation for intermittency based on the Reynolds-averaged quantities eliminated the need for the wall function and thus $k-\varepsilon-\gamma$ model could be applied to complicated wall bounded shear flows.

Recently Suzen and Huang (2000) developed an intermittency based transition model by combining two intermittency equations (Stellant and Dick (1996) and Cho and Chung (1992)). Their transition model has turned out to be useful in predicting the bypass transition, however, in some test cases there still remain some discrepancies between the predictions and the experimental data. Brief description of some transition models appears in the following.

Byggstoyl and Kollmann Model.

Byggstoyl and Kollmann (1986) proposed a conditional $k-\varepsilon-\gamma$ model, in which the transport equation for intermittency (γ) was expressed as follows;

$$\frac{\partial\gamma}{\partial t}+u_j\frac{\partial\gamma}{\partial x_j}=-\frac{\partial}{\partial x_j}[\gamma(1-\gamma)(\tilde{\bar{u}}_j-\tilde{\tilde{u}}_j)]+S_\gamma \quad (1)$$

where

$$S_\gamma = -C_{g1}\gamma(1-\gamma)\frac{\overline{\widetilde{u_i' u_j'}}}{\tilde{\bar{k}}}\left(\frac{\partial \bar{\tilde{u}}_i}{\partial x_j}+\frac{\partial \bar{\tilde{u}}_j}{\partial x_i}\right) + C_{g2}\frac{\tilde{\bar{k}}^2}{\tilde{\bar{\varepsilon}}}\frac{\partial \gamma}{\partial x_j}\frac{\partial \gamma}{\partial x_j} - C_{g3}\gamma(1-\gamma)\left(\frac{\tilde{\bar{\varepsilon}}}{\tilde{\bar{k}}}\right) \tag{2}$$

with $C_{g1}=1.8, C_{g2}=0.15, C_{g3}=0.05$, where $\approx$ and $\simeq$ denote the turbulent and non turbulent zone, respectively. $\tilde{\bar{k}}$ was the kinetic energy in turbulent zone and a similar notation holds for other flow variables.

Cho and Chung Model

Cho and Chung (1992) developed a $k-\varepsilon-\gamma$ model for free shear flows. They coupled their intermittency equation with conventional $k-\varepsilon$ model. Their intermittency equation was

$$u_j\frac{\partial \gamma}{\partial x_j} = C_{g1}\gamma(1-\gamma)\frac{P_{k,s}+P_{k,n}}{k} + \rho C_{g2}\frac{k^2}{\varepsilon}\frac{\partial \gamma}{\partial x_j}\frac{\partial \gamma}{\partial x_j} - C_{g3}\rho\gamma(1-\gamma)\frac{\varepsilon}{k}\Gamma + \frac{\partial}{\partial x_j}\left[\sigma_\gamma(1-\gamma)\frac{v_t}{\sigma_g}\frac{\partial \gamma}{\partial x_j}\right] \tag{3}$$

where

$$P_{k,s} = -\overline{u_i u_j}\frac{\partial u_i}{\partial x_j} \quad (i \neq j) \qquad P_{k,n} = -\overline{u_i u_j}\frac{\partial u_i}{\partial x_j} \quad (i = j) \tag{4}$$

$$\Gamma = \frac{k^{\frac{5}{2}}}{\varepsilon^2}\frac{u_i}{(u_k u_k)^{\frac{1}{2}}}\frac{\partial u_i}{\partial x_j}\frac{\partial \gamma}{\partial x_j} \tag{5}$$

The modeling constants were as follows;

$$C_{g1}=1.6 \quad C_{g2}=0.15 \quad C_{g3}=0.16 \quad \sigma_g=1.0 \tag{6}$$

The transitional behavior was incorporated into the computation by modifying the eddy viscosity relation.

Suzen and Huang Model

Suzen and Huang (2000) proposed a transport equation for intermittency which blended Steelent and Dick (1996) and Cho and Chung (1992) model. Their intermittency equation was coupled with Menter's SST model. Their intermittency equation was written by the following equation,

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho u_i \gamma)}{\partial x_i} = (1-\gamma)[(1-F)C_0\rho\sqrt{u_k u_k}\beta(s) + F(C_1\gamma\frac{P_k}{k} - C_2\rho\gamma\frac{\varepsilon}{k}\Gamma)] + C_3\rho\frac{k^2}{\varepsilon}\frac{\partial \gamma}{\partial x_j}\frac{\partial \gamma}{\partial x_j} + \frac{\partial}{\partial x_j}\left[((1-\gamma)\gamma\sigma_{\gamma l}\mu + (1-\gamma)\sigma_{\gamma t}\mu_t)\frac{\partial \gamma}{\partial x_j}\right] \tag{7}$$

The modeling constants were

$$C_1=1.6, C_2=0.16, C_3=0.15, \sigma_{\gamma l}=\sigma_{\gamma t}=1.0, C_0=1.0 \tag{8}$$

Suzen and Huang mentioned that their transition model was able to reproduce the intermittency profile in the cross-stream direction. They incorporated the intermittency factor into the computation simply by multiplying the intermittency factor with eddy viscosity that was obtained from Menter's SST model. The model was tested against zero and varying pressure gradient cases.

NEW TRANSITION MODEL

A new intermittency transport equation is introduced in this paper, which is a modification of Cho and Chung model. The main objective of this model is to predict FST-induced bypass transition of wall bounded shear flows and at the same time reproduces the intermittency profile in the cross-stream direction. As mentioned above, the original Cho and Chung $k-\varepsilon-\gamma$ model (1992) was proposed for free shear flows, therefore for the application to wall bounded flows wall functions are required. The proposed intermittency transport equation is coupled with Myong-Kasagi $k-\varepsilon$ turbulence model (1988) with near wall functions. The model is designated for the predict flow transition under the influence of free stream turbulence and pressure gradients.

Intermittency Equation

The proposed intermittency equation is

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho u_i \gamma)}{\partial x_i} = C_{g1}\gamma(1-\gamma)\frac{P_k}{k} + \rho C_{g2}\frac{k^2}{\varepsilon}\frac{\partial \gamma}{\partial x_j}\frac{\partial \gamma}{\partial x_j} - C_{g3}\rho\gamma(1-\gamma)\frac{\varepsilon}{k}\Gamma + \frac{\partial}{\partial x_j}\left[\sigma_\gamma(1-\gamma)(\mu+\mu_t)\frac{\partial \gamma}{\partial x_j}\right] \tag{9}$$

The first term of the right hand side in Eq. (9) represents the production term, where $P_k = \mu_t\left(\partial U/\partial y\right)^2$ represents the production of turbulent kinetic energy by the shear stress. This term expresses the generation of γ owing to the production of the turbulent kinetic energy. The second term represents the increase of γ by the spatial inhomogeneity or gradient of γ itself. The third term of the model accounts for the effect of entrainment. This term, however, is negligible for most flows, where

$$\Gamma = \frac{k^{\frac{5}{2}}}{\varepsilon^2}\frac{u_i}{(u_k u_k)^{\frac{1}{2}}}\frac{\partial u_i}{\partial x_j}\frac{\partial \gamma}{\partial x_j} \tag{10}$$

is interpreted as a non- dimensional parameter and is measure of the change in the intermittency due to entrainment (Cho and Chung, 1992). The last term represents the diffusion term. The role of diffusion term is to allow a gradual variation of γ towards zero in the free stream.

The present model differs from the original version of Cho and Chung (1992) with respect to the diffusion term and empirical constants. We propose a new diffusion term which controls the gradual increase of intermittency in every streamwise location and a set of model constants numerically tuned for the wall bounded shear flows. Since the original Cho and Chung model constants were selected only on a basis of plane jet experiment but the present model deals with the wall bounded shear flows, so the rearrangement of model constants was of great importance.

Any sink term did not exist in original model of Cho and Chung and a destruction effect is embodied by decreasing the model constant C_{g1} associated with the first source term (See Eq. (9)). In the present model, the value of C_{g1} is 0.19, whereas the original constant was 1.6. The model constants C_{g2} = 0.10 and C_{g3} = 0.01 are proposed instead of original constant values, C_{g2} = 0.15 and C_{g3} =0.16. Such constants control the transition lengths for higher turbulence intensity cases. All constants are selected through some numerical experiments. With these new constants, the proposed model with intermittency factor can capture the laminar and turbulent zone more properly than before, as will be shown in the next section.

The proposed empirical constants for the intermittency equation are

$$C_{g1} = 0.19, C_{g2} = 0.10, C_{g3} = 0.01, \sigma_{\gamma} = 1.0 \tag{11}$$

Baseline Turbulence Model and Onset Location.

For the prediction of turbulent quantities, the two-equation $k-\varepsilon$ turbulence model of Myong- Kasagi (1988) was chosen. Which is quite accurate in predicting the near wall quantities. Myong-Kasagi model is expressed as follows;

$$\rho u_j \frac{\partial k}{\partial x_j} = P_k - \rho\varepsilon + \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}], \tag{12}$$

$$\rho u_j \frac{\partial \varepsilon}{\partial x_j} = c_{\varepsilon 1} f_1 \frac{\varepsilon}{k} P_k - c_{\varepsilon 2} f_2 \rho \frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_\varepsilon}\}\frac{\partial \varepsilon}{\partial x_j}] \quad . \tag{13}$$

Eddy viscosity is calculated by

$$\mu_t = c_\mu f_\mu \frac{k^2}{\varepsilon} . \tag{14}$$

The following functions account for the near wall effects.

$$f_1 = 1.0 \tag{15}$$

$$f_2 = \left[1 - \frac{2}{9}\exp\{-(R_t/6)^2\}\right] \times \left\{1 - \exp(-y^+/5)\right\}^2 \tag{16}$$

$$f_\mu = (1 + 3.45/\sqrt{R_t}) \times \left[1 - \exp(-y^+/70)\right] \tag{17}$$

The model constants of the Myong-Kasagi model are

$$c_\mu = .09, c_{\varepsilon 1} = 1.4, c_{\varepsilon 2} = 1.8, \sigma_k = 1.4, \sigma_\varepsilon = 1.3 \tag{18}$$

The intermittency concept was incorporated into the computation by modifying the expression for the eddy viscosity as follows;

$$\mu_t^* = \left[1 + c_{\mu g}\frac{k^3}{\varepsilon^2}\gamma^{-3}(1-\gamma)\frac{\partial\gamma}{\partial x_k}\frac{\partial\gamma}{\partial x_k}\right]\mu_t \ , \tag{19}$$

where the constant is $c_{\mu g}$ = 0.10. The above expression for the eddy viscosity was originally proposed by Cho and Chung (1992) to account for the effect of outer irrotational fluid motion. The eddy viscosity given by Eq. (19) reduces to the fully turbulent flow, where $\gamma = 1.0$.

One of the important points associated with the intermittency-based turbulence model is to specify the transition onset point properly since the intermittency transport equation does not feature a capability to predict the transitional behavior of boundary layer. This study employed the well known Abu-Ghannam and Shaw (1980) correlation for determining onset location, which is given as follows;

$$\mathrm{Re}_{\theta_t} = 163 + \exp(6.91 - Tu) \ , \tag{20}$$

where Tu is turbulence intensity and Re_{θ_t} is the Reynolds number based on momentum thickness at onset location. Before the onset location, the production term of turbulent kinetic energy was set to be zero inside the boundary layer.

NUMERICAL SIMULATION

The computations were performed by use of the FVM-based boundary layer code, which was originally developed by Schmidt and Patankar (1988) and modified for the purpose of this study, where the function of PTM (Production Term Modification) in the code was deactivated and the above-mentioned intermittency equation was incorporated instead. Only a brief description on the code appears in the following.

Initially intermittency γ was set to .001. On the solid wall γ was set to 1, and at the edge of the boundary layer γ was .001. The initial profile for the mean velocity (U) in the laminar flow regime was prescribed by the Pohlhausen-profile and the temperature was assumed to vary in a linear manner with the velocity. The initial profile of k was assumed to show a quadratic increase with the wall distance from the wall. In the free stream k was set to $3/2(U_e Tu)^2$, where U_e was the velocity at the edge of the boundary layer. The initial distribution of dissipation was calculated from the relation $\varepsilon = Ak\partial U/\partial y$; the parameter A was the constant. The grid system automatically adjusted to the growth of the boundary layer. In the computation, 175 grid points were allocated inside the boundary layer, expanding in the cross-stream direction from the wall to the free stream. More than 15 control volumes usually existed within the viscous region $y^+ < 10$ of fully turbulent boundary layer.

RESULTS AND DISCUSSION

Test cases have been presented in this paper, including the ERCOFTAC (Savill, 1993a, 1993b) T3 series of flat plate zero pressure gradient experiments, heat transfer experiment of Blair and Werle (1980, 1981) for flat plate zero pressure gradient and favorable pressure gradient and turbine blade experiment of Daniel and Browne (1981). All of them are commonly used as benchmark for validating any transition model. In all computations, the inlet turbulent kinetic energy was determined by the experimental free stream turbulence level. The onset of transition was specified according to the correlation of Abu-Ghannam and Shaw (1980) for all cases tested in this study.

Test Cases of T3 Series.

In T3 series the first three cases (T3A-, T3A, and T3B) are zero pressure gradient ones with free stream turbulence intensity 1%, 3% and 6%, respectively. Comparisons were performed for these cases among the experimental data and the predictions using the new transition model, conventional turbulence models of Launder -Sharma $k-\varepsilon$ model (1974), $k-\omega$ model of Wilcox (1993) and Suzen-Huang $k-\varepsilon-\gamma$ model (2000). Figures 1 and 2 show the surface skin friction coefficients C_f and shape factors H_{12} for T3A case. As can be seen in Figure 1, Launder-Sharma $k-\varepsilon$ model and Wilcox $k-\omega$ model predicted early transition, while Suzen-Huang $k-\varepsilon-\gamma$ model and the present model exhibited better performance in the prediction of the skin friction coefficients. It appears that the present model yielded an improved agreement with the experiment in comparison with that of the Suzen-Huang model. Figure 2 illustrates that any models used in this study were not able to make an accurate prediction of the shape factor over the transitional zone. However, at least the present model exhibited a better predicting capability than the Suzen-Huang model.

The second test case of T3 series was T3A- case where the free stream turbulence intensity was 1%. Since the value of 1% free stream turbulence is regarded as a lower limit that can triggers bypass transition, this test is a tough one for any transition models. In this sense, as shown in Figure 3, the present model works better than the model of Menter et al. (2004), which may be one of the sophisticated bypass transition models.

The third test case of T3 series was the T3B case. This test case is also for flat plates zero pressure gradient flow with free stream turbulence intensity 6 % at the leading edge. Due to this higher free stream turbulence intensity, the boundary layer experienced very early transition. Figure 4 clearly demonstrates that the prediction by the present model matched the experimental skin friction coefficient more adequately than any other models employed in this study. Again the Wilcox model and Launder-Sharma model yielded much prompted transition and the model of Suzen and Huang predicted slightly delayed onset of transition. Since Suzen and Huang (2000) did not give any idea on the reason of this discrepancy, it is not clear why their model failed to make an accurate prediction of this case of the bypass transition. One of the possible explanations the present authors can imagine is that their year 2000 model have to be fine-tuned, especially for higher free stream turbulence cases.

Test Cases of Blair and Werle.

The present model has been applied to the test cases examined by Blair and Werle (1980, 1981) about transitional boundary layers on a flat plate with heat transfer under different levels of free stream turbulence intensity with and without pressure gradients. Note that there was an unheated zone just downstream of the leading edge of the plate. For the flat plate zero pressure gradient cases, free stream turbulence intensities are 1.4% (grid 1), 2.7% (grid 2) and 6.2% (grid 3) at the leading edge, respectively.

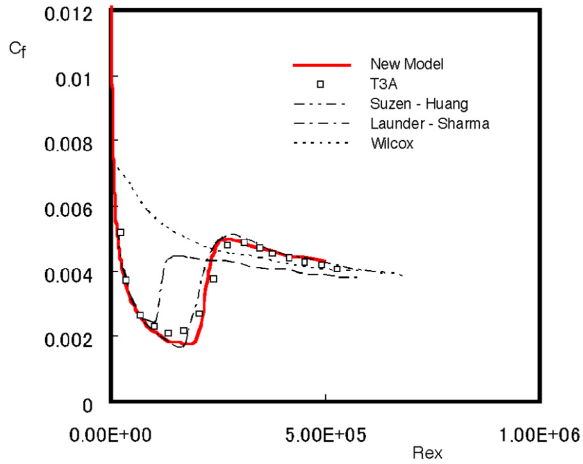


Figure 1 Surface skin friction coefficients for the T3A case, showing the comparison among the experimental data and several calculated results

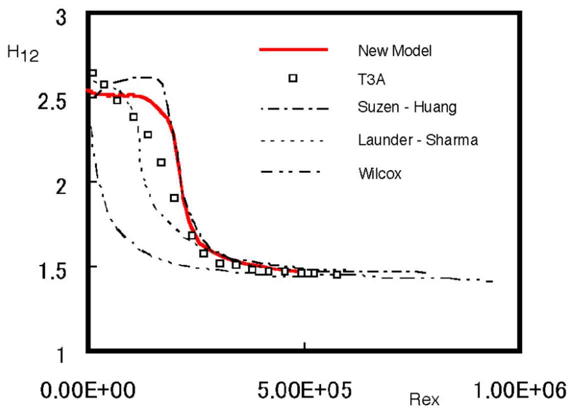


Figure 2 Shape factors for the T3A case, showing the comparison among the experimental data and several calculated results

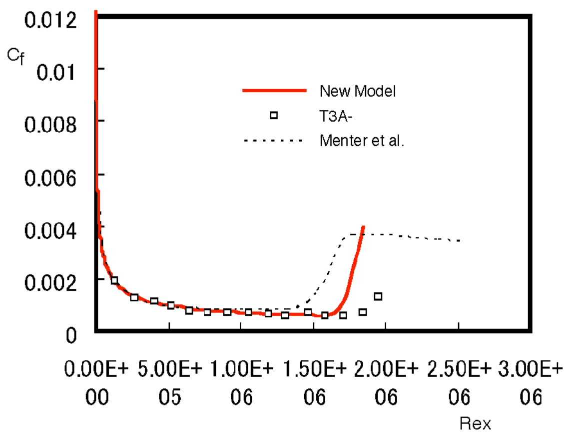


Figure 3 Surface skin friction coefficients for the T3A- case, showing the comparison among the experimental data and two calculated results

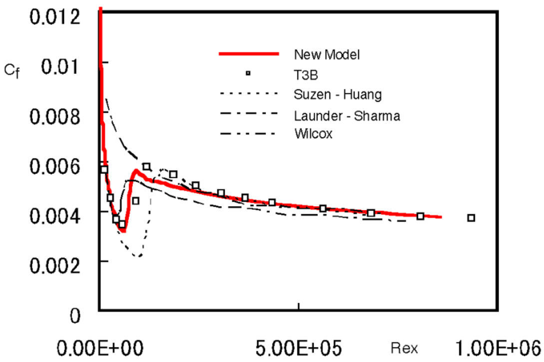


Figure 4 Surface skin friction coefficients for the T3B case, showing the comparison among the experimental data and several calculated results

In Figure 5, the calculated Stanton numbers are plotted against x ; the distance from the leading edge of the flat plate for grid1, grid2 and grid3 cases, respectively. Reasonable agreement was obtained for grid 1 and grid 3 cases, whereas very early transition was predicted for grid 2 case. For grid 3, the transition seems to have completed before the unheated zone ends. Figure 6 shows two test cases for transitional boundary layer with favorable pressure gradients of Blair and Werle (1981). In both cases, calculations are compared with the prediction of Launder-Sharma model. Figure 6 (a) is a low acceleration case. The acceleration parameter $K = \nu / U_e^2 \, dU_e / dx$ is $K = 0.2 \times 10^{-6}$ and the level of free stream turbulence is 2.1%. Figure 6 (b) shows the test case of high acceleration case where the acceleration parameter is 0.75×10^{-6} and the free stream turbulence intensity Tu is 2.1%. Compared to the case without any pressure gradient, the transition under the favorable pressure gradient took place further downstream and became more gradual. It appears that the present model performed fairly well to predict transitional behavior of the boundary layer under the favorable pressure gradient.

Test Cases of Daniel and Browne

The last test case of the current model is Daniel and Browne (1981) turbine blade experiment. In this case, the velocity data reported was functionally approximated by a series of polynomials to produce a smooth continuous representation of the data. Since the free stream turbulence was measured upstream of the blade and it was 4.2%, it was necessary to assess the free stream turbulence intensity very close to the blade leading edge. The present study adopted the value of 3.5% as the free stream turbulence intensity.

The calculated heat transfer coefficients on the suction side are shown in Figure 7. The calculation was also compared with the prediction of Schmidt and Patankar (1988) model. From comparisons it appears that the present model reasonably captured a general picture of the boundary layer transition on the blade suction side. However, the predicted transition was rather abrupt, while the Schmidt and Patankar model exhibited gradual increase in heat transfer during the transition zone and showed relatively better agreement with the measured data. It may be because they tuned their model to get an agreement with this experiment.

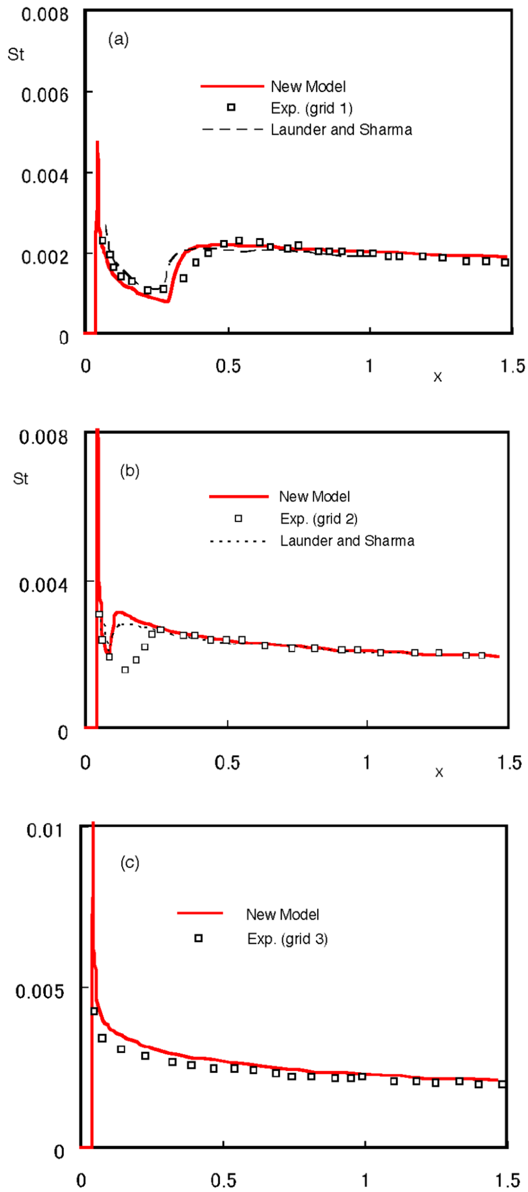
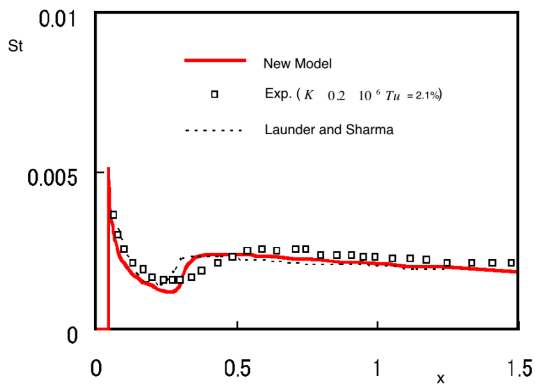


Figure 5 Stanton numbers for the Blair and Werle flat plate case with grid 1 ((a)), grid 2 ((b)) and grid 3 ((c)) under no pressure gradient



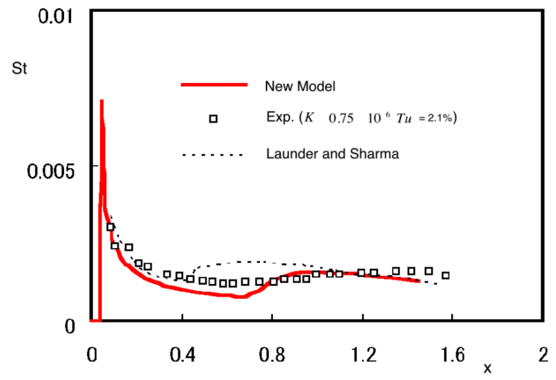


Figure 6 Stanton numbers for the Blair and Werle flat plate case under favorable pressure gradients

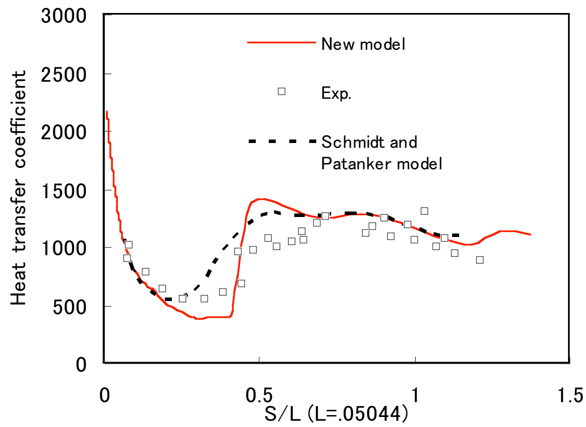


Figure 7 Heat transfer coefficients on the suction side of Daniel and Browne turbine blade

CONCLUDING REMARKS

A FST-induced bypass transition model, based on a dynamic transport equation for the intermittency factor in combination of Myong-Kasagi turbulence model, has been presented. For validation, the proposed model was tested against transitional boundary layer of flat plate zero pressure gradient case, transitional boundary layer with heat transfer for zero and adverse pressure gradient case and turbine blade test case. In all cases, the present model shows the good transitional behavior, especially in terms of surface skin friction coefficient. However, it has also turned out that the present model needs further modification to improve its capability for making a more accurate prediction of heat transfer characteristics. In addition, further study is now underway to implement the proposed model into a conventional CFD code.

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